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A drought rarity and evapotranspiration-based index as a suitable agricultural drought indicator

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ABSTRACT

Agricultural drought has a substantial impact on crop yields and, thus, food security within the context of global climate change. Therefore, efforts should focus on agricultural drought detection and monitoring. Agricultural drought is identified as unusually dry conditions in which severe water stress impedes crop growth. Thus, the crop water deficit *severity* and *rarity* are both key factors in agricultural drought detection and are rarely considered simultaneously in existing drought indices. To overcome this limitation, an integrated agricultural drought index (IADI) based on drought rarity and evapotranspiration is proposed. As an important grain production base, Northeast China has suffered from frequent droughts in recent years, demonstrating an urgent need for accurate drought monitoring. In this study, the superiority of the IADI as an agricultural drought indicator through the detection of the severity and rarity was tested using the drought disaster area (DDA) and grain yield, and its performance was compared to that of the evaporative drought index (EDI), an indicator that accounts for only the water deficit severity. The response of agricultural drought to meteorological drought and its impact on the grain yield were further analyzed. The results showed that (1) the IADI can effectively capture the drought variability and identify drought events by combining the detection of the severity and rarity. (2) The R^2 value between the DDA and IADI (0.72) was higher than that with the EDI (0.50), and the same result was found in a comparative analysis using the grain yield, showing that the IADI is a suitable indicator for agricultural drought assessment. (3) Severe and extreme meteorological droughts and extreme agricultural droughts in western Jilin and western Liaoning were more frequent than in other regions, highlighting the agricultural drought tendency and sensitivity to precipitation deficit in this region. (4) The impacts of agricultural drought on grain yield in three provinces of Northeast China vary greatly during the crop-growing period, with the most significant impacts occurring from May to July. Therefore, this period represents the critical crop water requirement period, and timely irrigation should be ensured during this period.

1. Introduction

Under the influence of global climate change, frequently occurring extreme meteorological events and their causes and impacts have drawn increasing attention worldwide (Millán, 2014; Powell and Reinhard, 2016; Trenberth et al., 2015). As one of the extreme meteorological events, drought caused by drastically reduced precipitation greatly affects agriculture production and social economic development, and its frequency, duration and spatial extent have exhibited increasing trends (Wilhite et al., 2014). Although agricultural management practices (such as irrigation) and crop improvements have led to increasing grain yields in recent years, agricultural drought still remains a potential threat to food security. Thus, accurately monitoring agricultural drought and analyzing its spatial-temporal characteristics are desperately needed to provide a basis for enacting effective measures to prevent potential disasters.

Meteorological drought is defined as a lack of precipitation during an extensive period of time, usually reflected by a significant negative deviation from the mean precipitation level (Mishra and Singh, 2010; Wilhite and Glantz, 1985). Agricultural drought is highly dependent on prevailing meteorological conditions and is significantly linked to meteorological drought. Agricultural drought occurs when the water supply cannot meet the crop water demand and is defined as a lack of soil moisture leading to crop damage (Mishra and Singh, 2010;

Abbreviations: IADI, integrated agricultural drought index; EDI, evaporative drought index; DDA, drought disaster area; PPA, percentage of precipitation anomaly index; NEC, Northeast China; DOY, date of year

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Sheffield et al., 2004; Wilhite, 2000; Wilhite and Glantz, 1985). Panu and Sharma (2002) claimed that if available water falls short of the normal crop requirement, then agricultural drought is likely to occur. This definition addresses two important aspects in agricultural drought identification. One is the imbalance between water supply and crop water requirements, and the other is the abnormal drought occurrence. Therefore, the *severity of the crop water deficit* and the *abnormal rare stress* are two key factors in agricultural drought detection. Whether existing drought indices are able to reflect the mutual occurrence of these two factors must be explored.

Most existing indices merely focus on one of the two aforementioned factors, either crop water deficit severity or stress rarity. The first index type describes drought severity at different times during a study period and it includes the vegetation condition index and the soil water deficit index (Kogan, 2001; Martínez-Fernández et al., 2016). However, even the same severity can have very distinct impacts on crops during different periods and in different regions due to spatial-temporal drought characteristics; therefore, indices that ignore corresponding rarity might lead to inaccurate drought detection. The second index type describes drought rarity using drought anomalies or frequencies based on long-term data series and it includes the soil moisture anomaly and the soil moisture frequency quantile index (Sheffield et al., 2004; Spennemann et al., 2015). This type of indicator is more feasible for regions with high inter-annual drought variability where the drought conditions can be reflected by the unusual status. However, whether the corresponding water deficit indeed impedes crop growth cannot be reflected. In regions with low inter-annual drought variability, events that are rare but similar to the normal state without impeding crop growth might be overestimated as droughts. No agricultural drought occurs when the crop water deficit is large but the severity is commonly observed, whereas no agricultural drought occurs either when the water deficit is rare but it does not impede crop growth. Therefore, the above two types of indices, which account for either water deficit severity or drought rarity, cannot comprehensively reflect drought conditions, and an integrated index that takes both into account is needed for accurate drought identification.

Although many types of indices have been developed based on meteorological factors (Kogan, 1995; Pai et al., 2011; Stagge et al., 2015; Thomas et al., 2016), soil water conditions (Chandrasekar and Sesha Sai, 2015; Martínez-Fernández et al., 2016), and vegetation growth status (Kogan, 2001; Sandholt et al., 2002; Sholihah et al., 2016), it is still difficult to find an index suitable for agricultural drought detection. Indices based on meteorological factors indeed reflect meteorological drought rather than agricultural drought because they do not consider the underlying surface conditions. Indices based on soil moisture require spatial-temporal continuous data. Soil moisture data provided by observation sites are always point-scale measurements; thus, the spatial heterogeneity at a large scale cannot be well described. Remote sensing makes it possible to monitor soil moisture at large spatial scales but it determines only the surface soil moisture, usually at depths of 0–5 cm, which is much shallower than crop root zone, and this kind of data struggle to meet the requirements of agricultural drought monitoring. Indices based on the vegetation growth status can be divided into two categories. Certain indices identify crop water stress via physiological growth observations, although the growing status cannot be quantified and is easily influenced by the personal judgment of the measurer. Other indices have been developed based on crop growth indicators from remote sensing, such as the normalized difference vegetation index or leaf area index, but the short time series of remote-sensing data remains a great problem.

The development of agricultural drought is a complex process involving various factors that can contribute to crop growth, including meteorological conditions, crop biological characteristics and soil properties. However, the indices mentioned above generally neglect the physical mechanism of the atmosphere-soil-crop continuum. Therefore, it is necessary to include as many of the contributing factors during crop growth period as possible (Wilhite, 2000). Crop water requirement under these comprehensive influences can be reflected through *evapotranspiration*, which is a significant process that drives the energy and water exchange between the atmosphere and the land surface (Mishra et al., 2015; Yao et al., 2011). A variety of indicators based on evapotranspiration have been developed for agricultural drought monitoring, such as the Palmer drought severity index (Palmer, 1965) and standard precipitation evapotranspiration index (Vicente-Serrano et al., 2010). Reference crop evapotranspiration represents the maximum crop water requirement and corresponds to conditions when sufficient soil water is available to meet the crop growth requirements. Actual evapotranspiration represents actual crop water consumption, and it will fall below the reference evapotranspiration rate if soil water is limited. Indicators that combine reference and actual evapotranspiration can reflect crop water equilibrium conditions and the soil moisture response to surface dryness (Kalma et al., 2008; McVicar and Jupp, 1998; Stagge et al., 2015; Wanjura et al., 1990). Therefore, an indicator based on evapotranspiration deficit was selected in this study to further develop an integrated drought index.

The objectives of this work are to (1) develop an integrated index that combines the crop water deficit severity and rarity to comprehensively reflect the drought characteristics and effectively monitor agricultural drought events; (2) evaluate the feasibility of the proposed integrated index for agricultural drought monitoring by comparing it with an index that represents only the crop water deficit severity; and (3) analyze the responses of agricultural drought to precipitation deficit and derive the critical period for crops when agricultural drought exerts the greatest impact on the grain yield.

2. Materials and methods

2.1. Study area

Heilongjiang, Jilin and Liaoning provinces, located in Northeast China (NEC), are selected as the study area for the current study (as shown in Fig. 1). This area extends from 38°43′ to 53°33′ in latitude and from 118°53′ to 135°05′ in longitude, with a total area of 790,000 km^2. With flat terrain and fertile soils, the central portion of NEC is one of the three major black soil areas in the world (Wang et al., 2015). NEC is located in a continental monsoon climate, where precipitation decreases gradually from southeast to northwest, with an annual average of 400–1000 mm. With a cold and long winter and mild and humid summer, the study area has an annual average temperature of −5 to 10 °C. The accumulated temperature above 10 °C is 1500–3700 °C, and the frost-free period lasts for 160–200 days. These natural conditions form a suitable environment for the growth of crops and make NEC an important grain production region in China. The intensity, duration and frequency of drought in NEC have exhibited increasing trends, suggesting that the area affected by drought will continue to expand (Wang et al., 2011). Thus, the study area, which relies on rain for agriculture production, has become increasingly vulnerable to agricultural drought (Yang et al., 2015). Therefore, it is of vital importance to develop a feasible agricultural drought index and to investigate the spatial-temporal drought characteristics in NEC.

2.2. Data

2.2.1. Precipitation data

Precipitation data were used to calculate the percentage of precipitation anomaly index (PPA) in the study area. The data were obtained from the China Meteorological Forcing Dataset (CMFD) supplied by the Institute of Tibetan Plateau Research, Chinese Academy of Sciences. This dataset has a spatial resolution of 0.1° and a temporal resolution of 3 h, and precipitation data from 2000 to 2010 were used in this paper.